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# Electrical Rating—Long-Term Performance Potential of Photovoltaic Systems

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Additional information is available at the end of the chapter

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## Abstract

Owing to diverse photovoltaic technology and dynamic nature of meteorological data, a number of factors affect the performance of photovoltaic systems. The highly efficient concentrated photovoltaic (CPV) system can only respond to beam radiations of solar energy, unlike stationary silicon-based conventional photovoltaic (PV) panels. The availability of solar energy, and share of beam/diffuse radiations, varies from region to region, depending upon weather conditions. However, the rated performance as instantaneous maximum efficiency at STC (standard testing conditions) or NOCT (nominal operating cell temperature) in the laboratory, does not depict the true system performance under changing field conditions. The energy planners are interested in actual field performance, in terms of total delivered energy. Therefore, despite highest efficiency, CPV installations seem to be limited to desert regions, with high beam radiations availability and favorable working conditions. In this chapter, the performance potential and feasibility of CPV system is reported for long term operation in tropical weather conditions, in terms of proposed electrical rating parameter, giving total energy delivered as kWh/m<sup>2</sup>.year. From 1-year field operation of two in-house built CPV units, electrical rating of 240.2 kWh/m<sup>2</sup>.year is recorded for CPV operation in Singapore, the first ever reported CPV performance in this region, which is two folds higher than the stationary PV.

**Keywords:** electrical rating, CPV, concentrated photovoltaic, long term performance, solar tracker, MJC

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## 1. Introduction

For the sustainable future environment, the renewable energy sources have been hailed as promising solution for primary energy supply. The rise in the global temperature can be

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expected to reach to an alarming level if the dependency on fossil fuels is unabated [1–5]. Solar energy is believed to be the only renewable energy source with highest energy potential among all energy sources, which is many time than the global energy demand [6, 7]. However, to solar energy useful energy, photovoltaic systems provide the simplest configuration to produce electricity by the direct utilization of solar radiations [8–10].

The photovoltaic market is having a huge diversity of photovoltaic technology which is ranging from simple single junction, non-concentrating, stationary flat plate panels, to advanced, multi-junction cell based concentrated photovoltaic systems. Such diversity depicts many different system configurations with different working conditions and parameters. The third generation multi-junction solar cell (MJC) concentrated photovoltaic (CPV) system provide highly efficient photovoltaic technology, available hitherto [11]. As we know, solar energy consists of two type of radiations i.e. beam and diffuse. Concentrated photovoltaic system relies onto low cost solar concentrators which can only respond and concentrate solar beam radiations [12] onto the smaller area of solar cell, unlike flat plate PV panels which can respond to both beam and diffuse part of solar radiations. The share of beam radiations in coming energy depends upon the sky conditions and the local climate. As solar concentrators can only respond to beam radiations, therefore, the conventional CPV systems were designed as gigantic unit which huge solar tracking unit, to be installed in the open desert regions. The main reason for such desert region design and application, was due to the clear sky condition with high beam share which is ideal for CPV.

The manufactures of PV and CPV system only furnish the catalogues of such system with rated and maximum capacity. Such rated performances are measured under controlled laboratory conditions and at certain optimum energy input. The standard testing procedure for such rated performance measurements are carried out under STC (Standard Testing Conditions, IEC 60904-3) parameters or NOCT (Nominal Operating Cell Temperature, IEC 61215 and IEC 61646) conditions [13]. Such laboratory testing conditions are totally different that the actual field operating conditions [14, 15]. The field conditions fluctuate throughout the day with different intensities. There are three factors responsible for such fluctuating field conditions. Firstly, the share of beam and diffuse radiations in the received solar energy is changing throughout the day, due to clod cover and changing sun position. Secondly, the cell operating temperature changes drastically throughout the operation due to daily and seasonal change in ambient temperature. Thirdly, the dust particles present in the air [16] and the dust storms reduce the incoming solar radiations thereby, affecting the performance output of photovoltaic modules. However, the customers and plat designers are interested in the actual output of the system which can be obtained during their filed operation and life period. Therefore, the rated performance of CPV and PV systems, available in the overwhelming catalogues of manufacturers, does not reflect the true performance of the system as the rated conditions are far different than the actual conditions [17, 18].

In addition, every system requires different operating conditions. Therefore, despite being highly efficient photovoltaic technology, concentrated photovoltaic (CPV) are only targeted to be installed in open desert regions due to favorable conditions as due to clear sky, these regions have high beam radiation share in solar energy and CPV can only respond to beam radiations.

Therefore, it can be understood that the feasibility and potential of a system cannot be judged by rated performance parameters and conditions. The real field output of the system must be the real performance indicator of the system and to be used by the plant designers and the customers. Therefore, this chapter introduces the long term electrical rating as true performance parameter of Photovoltaic system. In addition, the real field performance data of CPV and conventional PV systems is also presented, for tropical weather condition, to compare and analyze the performance under different scenarios of electrical rating method.

## 2. Development of CPV system

In order to investigate the performance of the CPV system, two CPV units, one with double reflective cassegrain based concentrating assembly and other with Fresnel lens based concentrating assembly, were developed with two axis solar tracker.

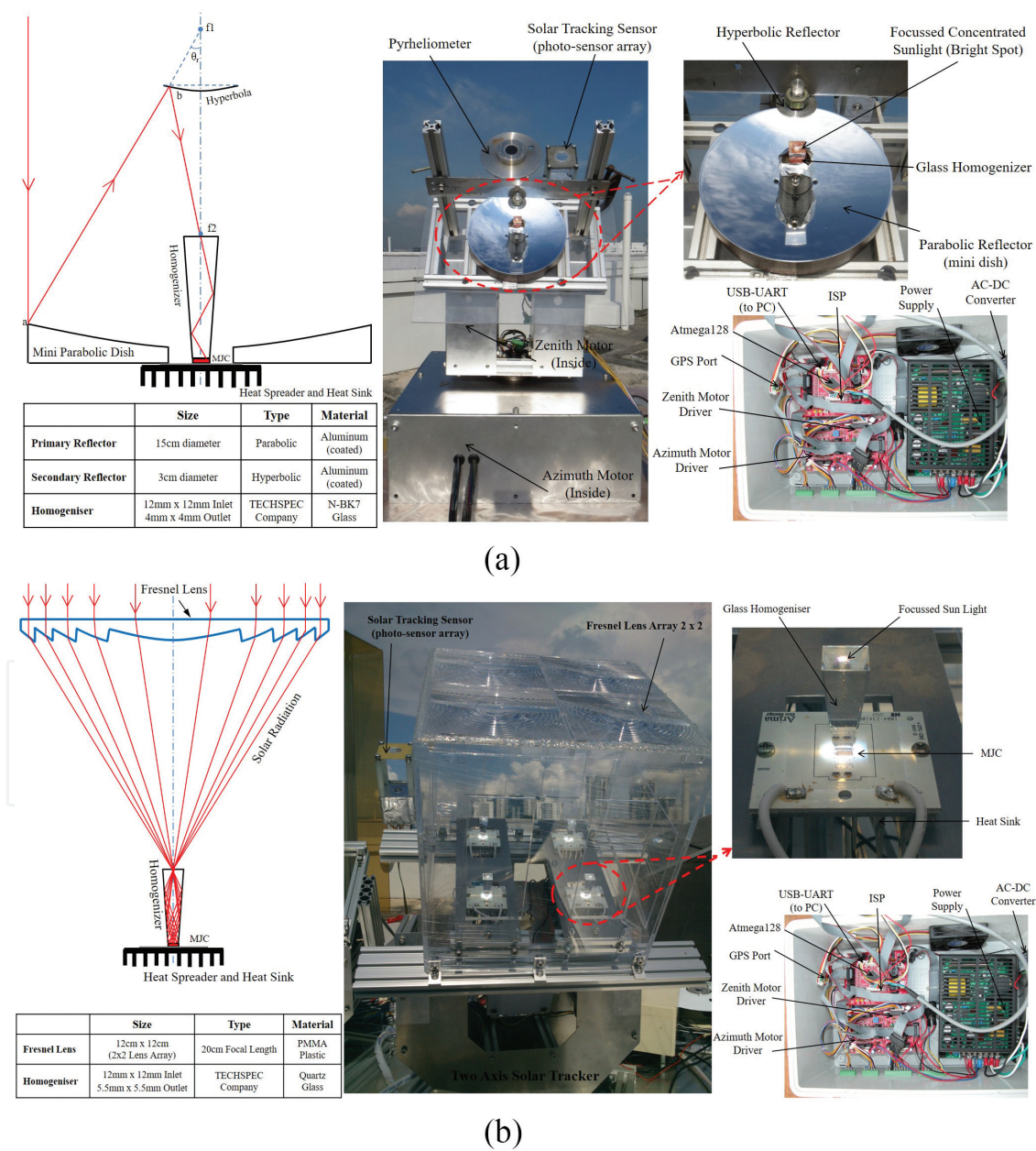
**Figure 1** shows the schematic and the concentrating assembly arrangement of the two developed CPV systems for current study. The CPV unit shown in **Figure 1(a)**, named as mini dish CPV unit, is using cassegrain arrangement of parabolic and hyperbolic reflectors, for double stage concentration. The other CPV unit, named as Fresnel lens CPV unit, as shown in **Figure 1(b)**, is designed for single stage concentration by using Fresnel lens as solar concentrator. In both designs, the solar radiations are concentrated at the inlet of glass homogeniser, which further guides and uniformly distributes the solar radiations onto multi-junction solar cell (MJC), placed at the outlet aperture of the glass homogeniser. The back side of the MJC is attached to heat spreader and heat sink, for heat rejection, in order to keep cell temperature within the operational range. For Fresnel lens based CPV unit, the glass homogeniser is placed at the focal point of the Fresnel lens. While for mini dish CPV unit, primary parabolic reflector first try to concentrate solar radiations at its focal point  $f_1$ , however, due to secondary hyperbolic reflector, the solar radiations are again reflected to be focused at its focal point  $f_2$ , where glass homogenizer is placed.

The specifications and materials of the developed CPV prototypes are also shown in **Figure 1** [12]. The concentrated light spot that can be seen at center of the glass homogenizer, verifies the perfect design of the concentrating assemblies. Both CPV modules are mounted onto the aluminum frame of two axis solar tracker, controlled by atmega128 microcontroller. The developed CPV systems have acceptance angle of  $0.3\text{--}0.4^\circ$  for mini dish and  $0.6\text{--}0.7^\circ$  for Fresnel Lens CPV unit. The control box of the two axis solar tracker, as shown in **Figure 1**, is based upon AVR ATmega128 microcontroller which is connected to two stepper motor drivers, power supply and GPS module. The developed two axis solar tracker works on a hybrid tracking algorithm, astronomical and optical tracking. At first, astronomical tracking is executed according to azimuth and zenith angles computed through solar geometry, as explained in [19]. For astronomical tracking to compute azimuth and zenith angles, data regarding local latitude, longitude, date and time, is received through GPS. The calculated azimuth and zenith angles are then compared with the actual position of the tracker, with reference to north or south plane and horizontal plane. If the difference is more than the required tracking accuracy i.e.  $0.1^\circ$  then



the tracker is moved accordingly otherwise it remains stationary. The tracking algorithm and tracking path are shown in **Figure 2**. According to the tracking path, the solar tracker is always kept within the tracking accuracy of  $\pm 0.1^\circ$ . When astronomical tracking method completes, feedback from the solar tracking sensor is obtained based upon the actual position of sun, with sensitivity of  $0.1^\circ$ . The solar tracking sensor consists of an array of photo-sensors and if feedback from any of the photo-sensor is high, then tracker is adjusted accordingly otherwise it remains stationary, depicting tracker is accurately facing the sun. This tracking algorithm loop then starts again from the astronomical tracking.

To verify reliability and accuracy of the astronomical tracking algorithm, the calculated azimuth and zenith angles were compared with the azimuth and zenith angles data, obtained from Astronomical Applications Department of the U.S. Naval Observatory for January 1,



**Figure 1.** Developed prototypes of CPV system (a) mini dish CPV unit and (b) Fresnel lens CPV unit.

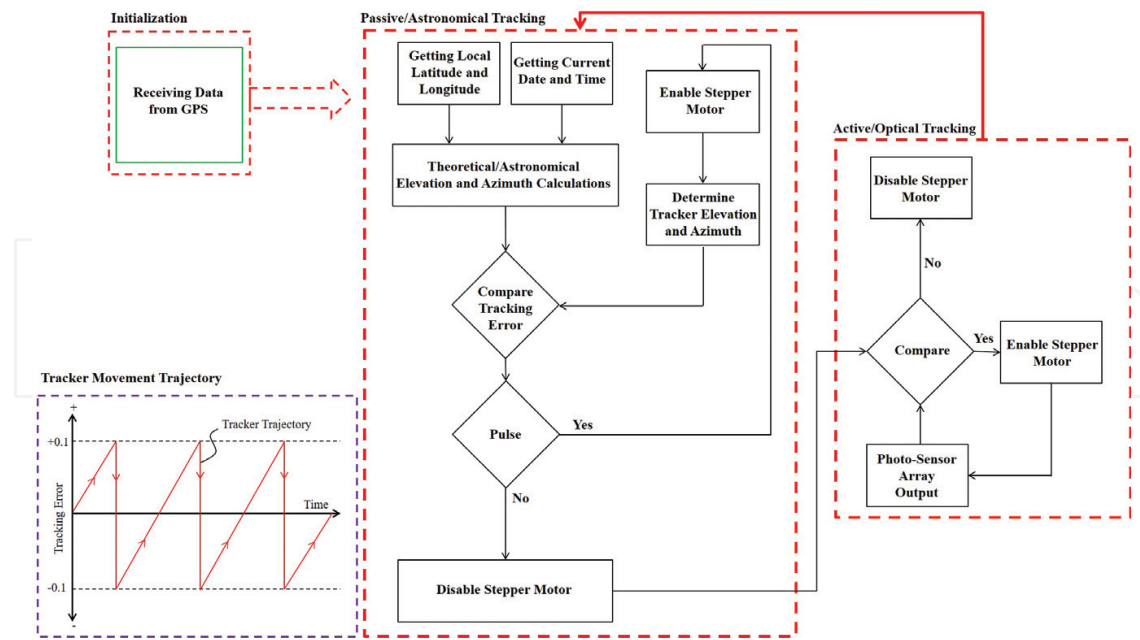


Figure 2. Hybrid tracking algorithm.

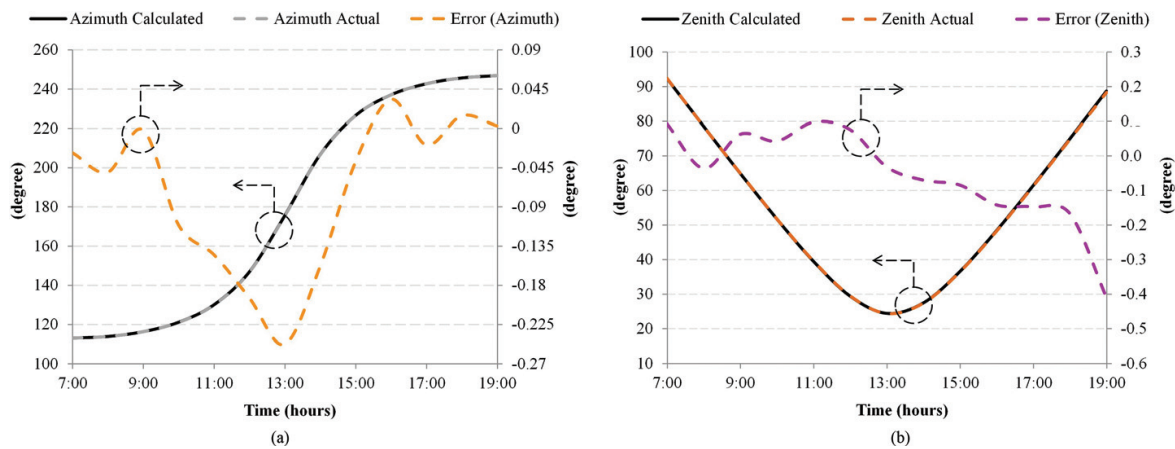


Figure 3. Comparison of calculated and actual (a) azimuth (b) zenith angles.

2015 [20] with latitude of  $1.299^{\circ}\text{N}$  and longitude of  $103.771^{\circ}\text{E}$  (for NUS EA-building). The comparison of the tracking angles is shown in **Figure 3**, for which calculated and obtained azimuth and zenith angle lines are overlapping. The difference in tracking angles is not more than 0.25 and 0.4 for azimuth and zenith angles respectively. This difference is within the acceptance angles of both of the CPV units and can be handled through solar tracking sensor.

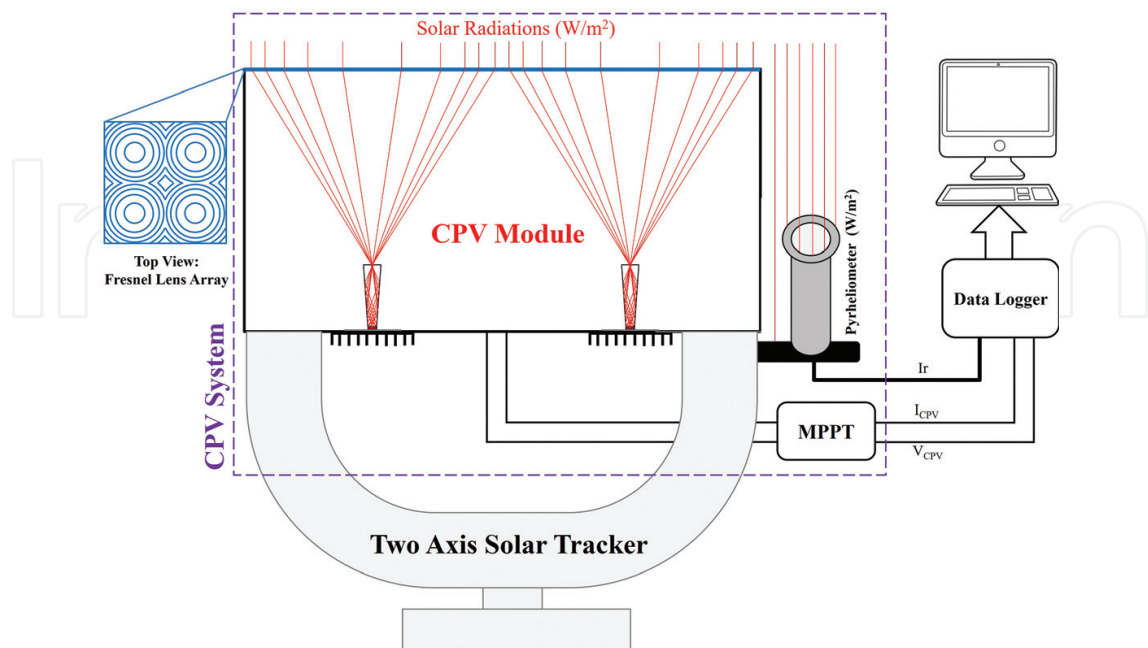
### 3. Testing methodology

In order to analyze the actual field performance of the CPV system and to compare it with the conventional stationary PV, irrespective of their operating conditions, total energy output of the system for long term period of operation is taken as the common reference to compare the

performance and feasibility of the photovoltaic technologies. For this purpose, an electrical rating parameter is proposed and used to demonstrate the long term performance of the photovoltaic system in terms of total energy output, expressed in  $\text{kWh/m}^2\cdot\text{year}$ . The main significance of comparison over total energy output, instead of instantaneous efficiency, is that it accommodates all of the effects of system operating condition, configuration and efficiency, and it is the main parameter of interest for the customers from any power plant. In addition, the normalization of energy output over per  $\text{m}^2$  area will help plant designers to determine the size of the plant as per required energy requirements. Furthermore, the consideration of long term performance comparison is to mitigate the effect of solar intermittency and weather condition as the average annual solar insolation and weather condition remain same. In current study, the system testing is carried out in tropical weather of Singapore, for 1 year from September, 2014 to August, 2015. Complete detail regarding the methodology of experiment and the calculation of electrical rating and its associated parameters, is discussed further in this section.

### 3.1. System description

The CPV system analysis is based upon the electrical power output, calculated from CPV current and voltage output through maximum power point tracking (MPPT). The CPV units were operated for whole day, from sun rise to sunset and the power output from the systems was recorded through Agilent data logger at an interval of 1sec. The solar energy input data of direct normal irradiance (DNI) was collected by using Pyrheliometer. The system description of current experimental setup is shown in **Figure 4**. To analyze the recorded data, the power output from the system and solar energy received were integrated over the whole day period by using OriginPro software, to obtain the total energy input and output of the system.



**Figure 4.** Experimental setup description of CPV system [12].

### 3.2. Electrical rating

To investigate short and long term performance of CPV system, monthly and overall electrical rating can be determined by using Eqs. (1) and (2).

$$\text{Monthly Electrical Rating, } R_{e,m} = \left( \sum_{j=1}^n E_i \right) \cdot \frac{365}{n} \quad \left( \frac{\text{kWh}}{\text{m}^2 \cdot \text{year}} \right) \quad (1)$$

$$\text{Overall Electrical Rating, } R_e = \left( \sum_{j=1}^m E_i \right) \cdot \frac{365}{m} \quad \left( \frac{\text{kWh}}{\text{m}^2 \cdot \text{year}} \right) \quad (2)$$

where 'n' represent the maximum number of days, for that particular month, and 'm' represents the overall total number of days for which the experiment was performed and data was recorded. The parameter 'E' represents the daily total electrical energy output of the CPV system, given by Eq. (3). Similarly, daily total solar energy received by CPV system is given by Eq. (4).

### 3.3. Daily electrical energy output and solar insolation

$$E = \int_1^t \left( \frac{V_{CPV} \cdot I_{CPV}}{A_C} \right) dt = \sum_{i=1}^t \left( \frac{(V_{CPV} \cdot I_{CPV})_i - (V_{CPV} \cdot I_{CPV})_{i-1}}{2 \times A_C} \right) \cdot S \quad \left( \frac{\text{kWh}}{\text{m}^2} \right) \quad (3)$$

$$D_m = \int_1^t (Ir) dt = \sum_{i=1}^t \left( \frac{(Ir)_i - (Ir)_{i-1}}{2} \right) \cdot S \quad \left( \frac{\text{kWh}}{\text{m}^2} \right) \quad (4)$$

where 'V<sub>CPV</sub>' and 'I<sub>CPV</sub>' are voltage and current of the CPV units at maximum power point, obtained from multi-junction solar cells, A<sub>C</sub> is the area of concentrator and 'Ir' represents the DNI received in W/m<sup>2</sup>. The parameter 't' represents the time of operation in seconds for that particular day and 'S' is scanning interval between two recordings, which is 1sec for current study.

### 3.4. System average DNI efficiency

Based upon the total daily energy input and output of the CPV system, daily, monthly and overall average efficiency of the system are given by Eqs. (5)–(7).

$$\text{Daily Average DNI Efficiency} = \frac{E}{D_m} \times 100 \quad (\%) \quad (5)$$

$$\text{Monthly Average DNI Efficiency} = \frac{\sum_{j=1}^n E_i}{\sum_{j=1}^n D_m} \times 100 \quad (\%) \quad (6)$$



$$\text{Overall Average DNI Efficiency} = \frac{\sum_{j=1}^m E_i}{\sum_{j=1}^m D_m} \times 100 \quad (\%) \quad (7)$$

### 3.5. System average GHI efficiency

As CPV system can only accept beam radiations of solar energy, so the average efficiency mentioned above is based upon the DNI input. In order to have comparison with the conventional stationary PV system, average efficiency based upon the global horizontal irradiance (GHI) is given by Eq. (8).

$$\text{Overall Average GHI Efficiency} = \frac{\sum_{j=1}^m E_i}{\sum_{j=1}^m GHI} \times 100 \quad (\%) \quad (8)$$

### 3.6. Percentage share of beam radiations

The percentage share of beam radiations received against global irradiance is given by Eq. (9).

$$\text{DNI Share} = \frac{\sum_{j=1}^n D_m}{\sum_{j=1}^n GHI} \times 100 \quad (\%) \quad (9)$$

### 3.7. CO<sub>2</sub> emissions saving

In addition, CO<sub>2</sub> emissions saving for each kWh electric produced, can also be computed by using the carbon emission factor provided by International Energy Agency (IEA) and is given by (10):

$$\text{CO}_2 \text{ Emissions Saving} = R_e \times 0.635 \quad \left( \frac{\text{kg}}{\text{m}^2 \cdot \text{year}} \right) \quad (10)$$

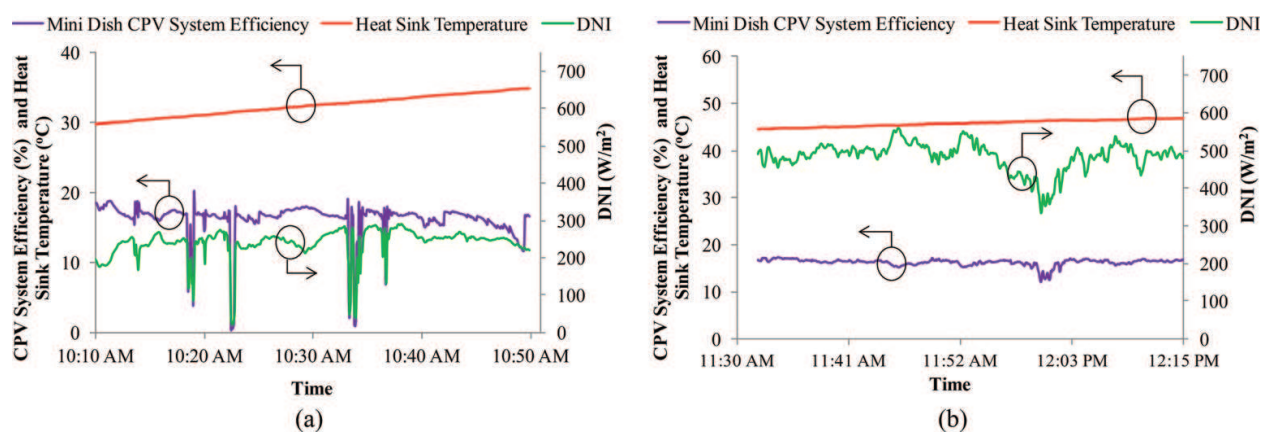
where 0.635 CO<sub>2</sub> tons/MWh<sub>e</sub> is the value for crude oil taken from International Energy Agency (IEA) [21], for calculations in current chapter. The value of CO<sub>2</sub> emissions saving depends upon the carbon emission factor which is different for different fuels and depends upon their calorific values.

## 4. Maximum performance characteristics of systems under comparison

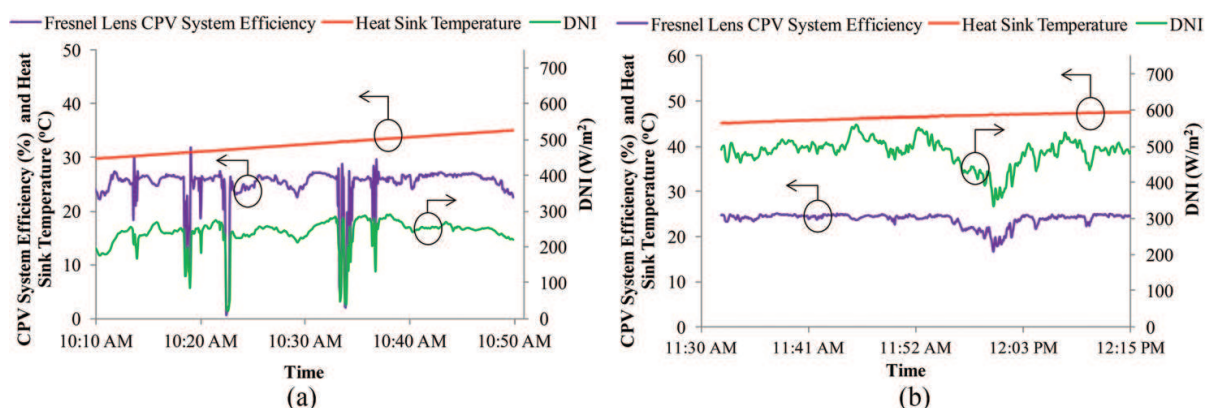
In this section, the characteristics, maximum performance rating and installed location of the systems under comparison is described. **Table 1** shows the maximum performance rating of the used multi-junction solar cell, by Arima Photovoltaic and Optical Co., and the developed CPV Units. The maximum efficiency of both CPV systems is based upon the real field testing at EA-Building NUS Singapore and the performance graphs with back plate or heat sink temperature, during testing, are shown in **Figures 5** and **6**.

Sr. no.	Photovoltaic technology	Performance
1	Multi-junction solar cell (InGaP/InGaAs/Ge)	Concentration ratio = 500 Efficiency = 39.5% @ 25°C cell temperature Efficiency = 35.2% @ 90°C cell temperature Concentration ratio = 100 Efficiency = 38.5% @ 25°C cell temperature Efficiency = 33.6% @ 90°C cell temperature
2	Fresnel lens CPV unit	Geometric concentration ratio = 476 Maximum module efficiency = 28% Tested at NUS EA-building rooftop
3	Mini dish CPV unit	Geometric concentration ratio = 492 Maximum module efficiency = 18% Tested at NUS EA-building rooftop

**Table 1.** Maximum performance rating of multi-junction solar cell and developed CPVs [12].



**Figure 5.** Mini dish CPV system performance. (a) Test 1 and (b) Test 2 [12].



**Figure 6.** Fresnel lens CPV system performance. (a) Test 1 and (b) Test 2 [12].

It can be seen that the Maximum efficiency of Fresnel lens CPV unit is same as commercial CPV systems i.e. 28%. For both CPV prototypes, same type of multi-junction solar cell is used. However, lower conversion efficiency of mini dish CPV unit is due to aluminum reflecting coating on both reflectors, which had lower reflectance due to surface imperfections, causing



**Figure 7.** Conventional monocrystalline, polycrystalline and thin film (CIS) PV systems at CITI (BCA), Singapore [22].

Sr. no.	Photovoltaic technology	Performance	Location
1	Mono-crystalline (16.86 m <sup>2</sup> )	17.2% @ STC [23]	CITI (BCA), Singapore.
2	Poly-crystalline (19.4 m <sup>2</sup> )	16.2% @ STC [24]	
3	Thin film (CIS) (21.27 m <sup>2</sup> )	17% @ STC [25]	

**Table 2.** Performance characteristics of conventional PV systems at CITI (BCA), Singapore.

lower optical efficiency of the mini dish concentrating assembly. The reason for testing the CPV efficiency at different time zones, is to show the effect of temperature on the system performance. It is evident from the **Figures 5** and **6** that the CPV efficiency is decreasing with increase in the heat sink temperature in the noon time, due to higher DNI received.

In order to show the feasibility and the potential of CPV system operation in tropical region, the performance of the CPV units is compared with the other conventional stationary PV system installed in Singapore, shown in **Figure 7**. The details of these PV units regarding their maximum rating, the cell type and the installed location, are given in **Table 2**.

5. Results and discussion

The field operating conditions in form of daily average ambient temperature and the solar energy input as direct normal irradiance (DNI) and global horizontal irradiance (GHI), are shown in **Figure 8** for the period of 1 year. The presented DNI data is the actual recorded measurements taken at the rooftop of NUS EA-building, Singapore with an interval of 1 s. The data was recorded for 1-year period from September 2014 to August 2015. The GHI and the daily average ambient temperature data were obtained from National Environment Agency (NEA) Singapore [26], for 3-year period from 2012 to 2014. However, the presented data is the 3-year average value for GHI and ambient temperature. From **Figure 8**, it can be seen that the

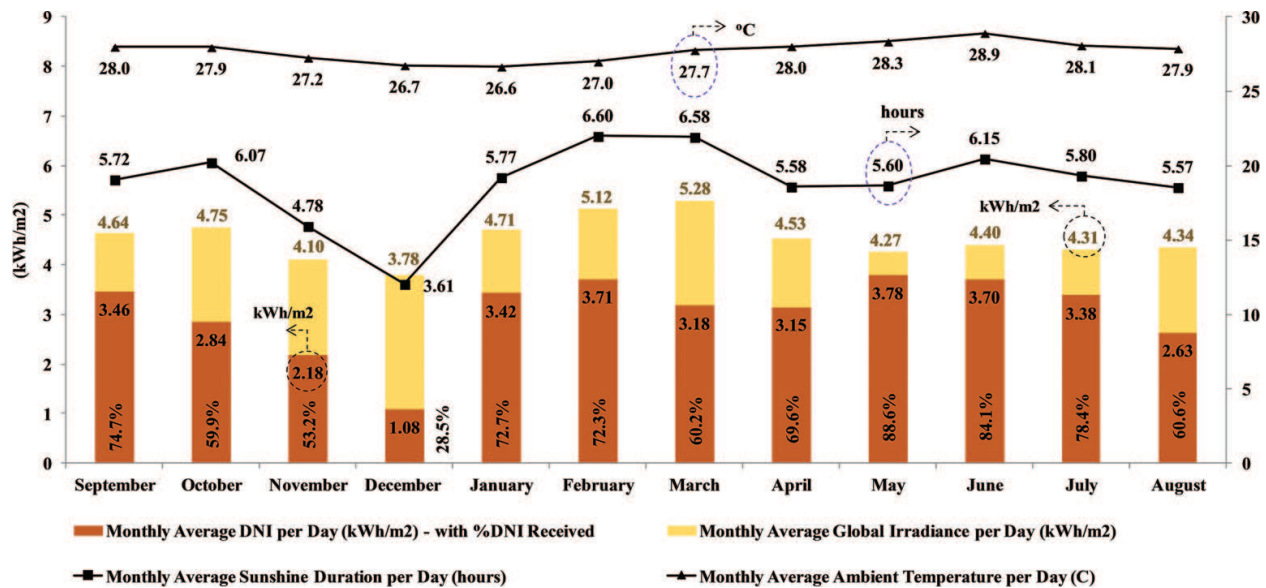


Figure 8. Monthly average values of solar irradiance (Global and DNI) and sunshine duration data per day [12].

longer sunshine period is observed for the month with larger amount of received solar energy. For March, the received GHI in  $\text{kWh/m}^2/\text{day}$  is highest with longest sunshine period. On the other hand, for the rainy season period of November and December, the lowest amount of solar energy was received, for tropical weather of Singapore.

The field performance potential of developed CPV systems in form of monthly average DNI efficiency and monthly electrical rating, against percentage of DNI share in total received solar energy, is shown in Figure 9. At first glance, it can be seen that the monthly average electrical rating is proportional to the direct normal irradiance share. For May and June, it can be ordered that the highest electrical rating value was recorded as 297.6 and 296.2  $\text{kWh/m}^2/\text{year}$  for Fresnel Lens CPV system and 235 and 227.2  $\text{kWh/m}^2/\text{year}$  for mini dish CPV system, respectively. It's due to larger share DNI in received solar radiations. On the other hand, for November and December, very poor output was recorded from both CPV systems due to low DNI availability. It is important to mention here that the main reason for higher electrical rating of Fresnel lens than the mini dish CPV, is due to its higher system efficiency as explained in Figure 5. The monthly average efficiencies of 22 and 16% were recorded for Fresnel lens and mini dish CPV systems, respectively. The highest efficiency was recorded for February, which is due to the longest sunshine duration and lowest ambient; the favorable conditions for CPV system.

In order to compare the field performance of CPV system with conventional flat plate PV panels, in tropical urban region, the electrical rating is presented for both developed CPV systems and three PV system, based upon single junction solar cells, installed at the rooftop of CITI (BCA), Singapore [27]. The yearly performance data is shown in Figure 10. The Fresnel lens CPV system showed the highest electrical rating of 240.21  $\text{kWh/m}^2/\text{year}$  which is about 2 folds higher than the conventional PV systems. The annual average efficiency of 22% was also recorded during 1-year operation. Such long term efficiency includes all of the performance affecting parameters and that is why, it provide most meaningful and reliable performance



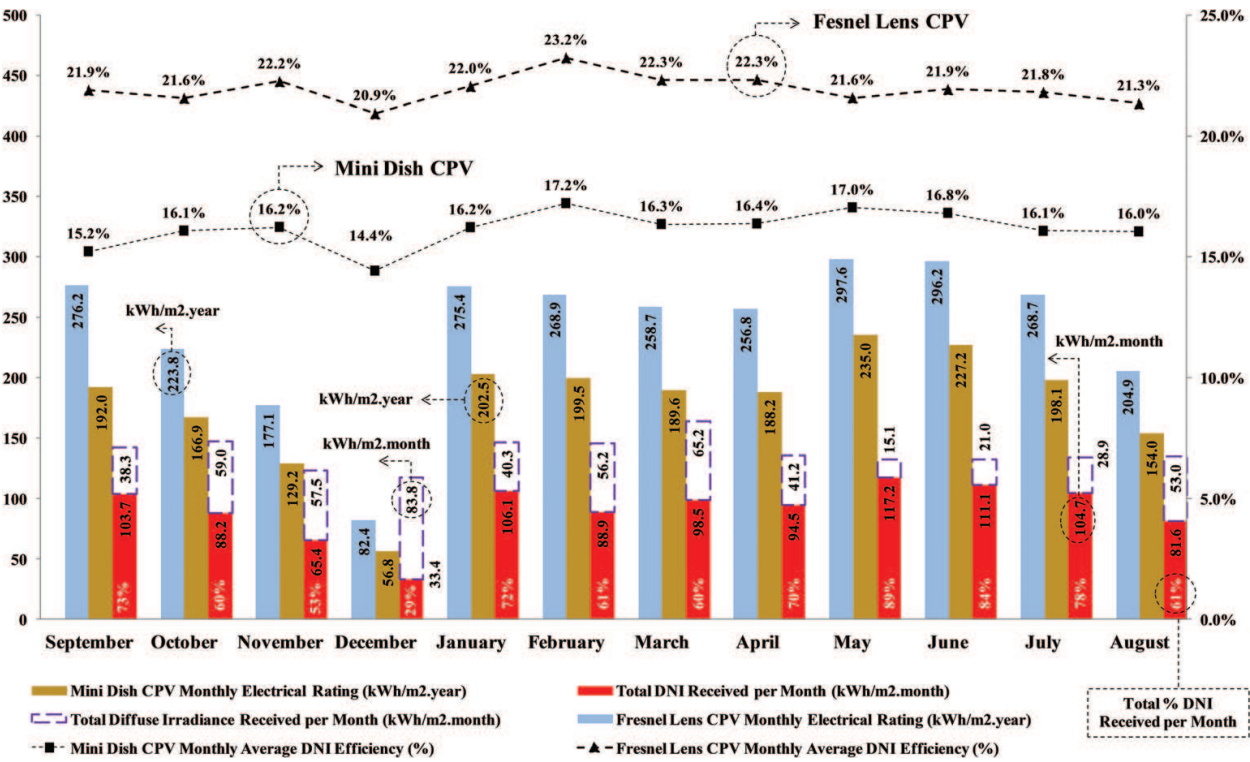


Figure 9. Monthly electrical rating and monthly average efficiency of CPV systems with the DNI received [12].

indicating parameter for photovoltaic systems, as compared to the instantaneous rated efficiency. It is important to mention here that the CPV system showed twice the power output than the conventional PV system, indicating the superiority and feasibility of CPV technology even in tropical region, other than the open desert fields.

So far, the presented efficiency of CPV system is based upon direct normal irradiance (DNI) as solar energy input. Because concentrated photovoltaic (CPV) system can only respond to beam radiations of solar energy. This means that another big portion of solar energy in form of diffuse radiations, which is very high in tropical climates, is not considered in the efficiency calculations of CPV as solar energy input. However, conventional PV systems can respond to both, beam and diffuse radiations. Therefore, in order to compare the performance of CPV with conventional PV, diffuse radiations must also be considered as solar energy input. For such scenario, based upon global horizontal irradiance, the GHI efficiency of photovoltaic systems is shown in **Figure 10**. An average solar insolation of 1700 kWh/m<sup>2</sup>.year is considered as global solar energy input to the photovoltaic system. The CPV system showed 14% GHI efficiency which is still 2 folds higher than conventional PV, even in tropical weather conditions. The summary of annual field performance of CPV systems is shown in **Table 3**. It can be seen that only 66.1% of total solar energy was received in form of beam radiations which were converted into electricity by CPV system, but still two times the power output of conventional PV. For comparison purpose, the long term energy output of conventional PV units, across the globe, is also given in **Table 4**.

**Figure 11** shows the plot of monthly electrical rating against monthly received solar energy, to analyze the synergy of proposed method of electrical rating. For CPV system, monthly electrical rating is plotted against received DNI. On the other hand, the overall electrical rating



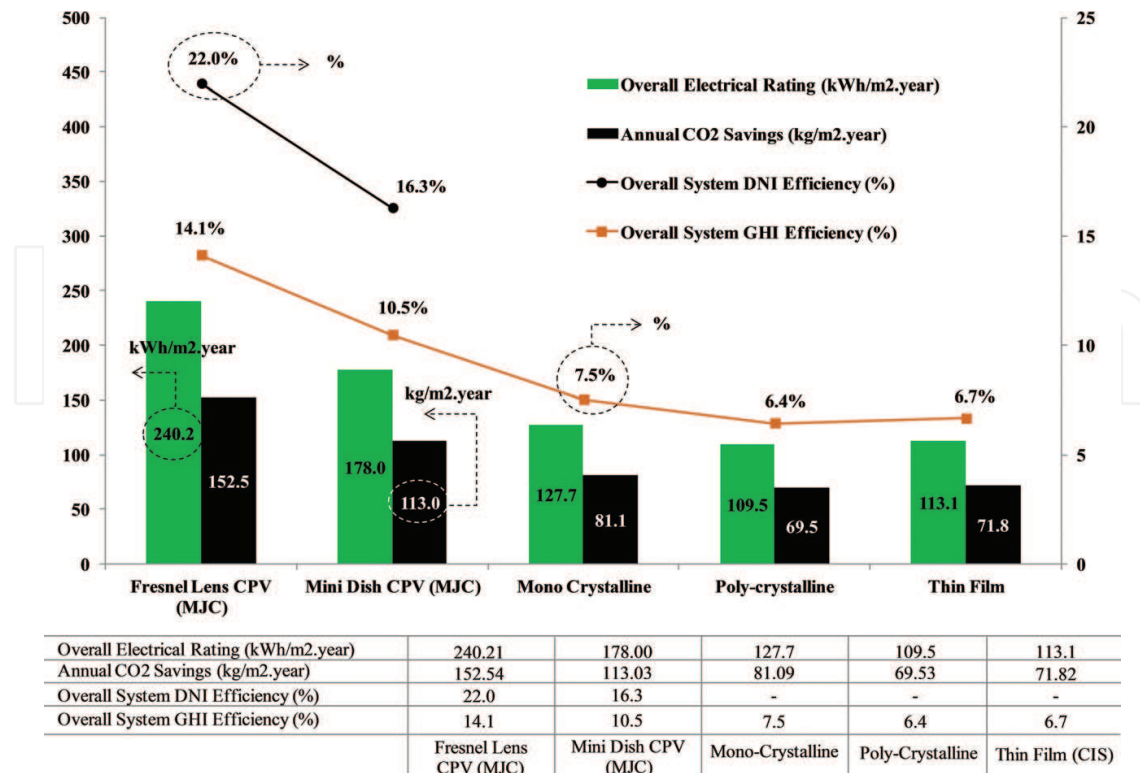


Figure 10. CPV systems and conventional PVs and their CO<sub>2</sub> savings comparison [12].

Month	Solar input			Fresnel Lens CPV		Mini Dish CPV	
	GHI*	DNI	DNI share	Total power delivered	Average DNI efficiency	Total power delivered	Average DNI efficiency
	GHI	D <sub>m</sub>		E		E	
	kWh/m <sup>2</sup> /month	kWh/m <sup>2</sup> /month	%	kWh/m <sup>2</sup> /month	%/month	kWh/m <sup>2</sup> /month	%/month
September	142.04	103.75	73.0	22.70	21.89	15.78	15.2
October	147.20	88.19	59.9	19.00	21.6	14.17	16.1
November	122.97	65.44	53.2	14.55	22.2	10.62	16.2
December	117.21	33.45	28.5	7.00	20.9	4.82	14.4
January	146.37	106.10	72.5	23.39	22.0	17.20	16.2
February	145.17	88.83	61.3	20.63	23.2	15.30	17.2
March	163.73	98.52	60.2	21.97	22.3	16.10	16.3
April	135.77	94.55	69.6	21.10	22.3	15.47	16.4
May	132.31	117.19	88.6	25.28	21.6	19.96	17.0
June	132.08	111.11	84.1	24.35	21.9	18.67	16.8
July	133.68	104.75	78.4	22.83	21.8	16.82	16.1
August	134.59	81.58	60.6	17.40	21.3	13.08	16.0
Annual Average	1653.12 kWh/m <sup>2</sup> /year	1093.46 kWh/m <sup>2</sup> /year	66.1%	240.2 kWh/m <sup>2</sup> /year	22.0%	178.0 kWh/m <sup>2</sup> /year	16.3%

\*from NEA [26].

Table 3. Summary of long-term (12 months) performance data of CPV systems [12].

Sr. no.	Plant location	Solar cell type	Average efficiency
1	JNU, JEJU, Korea	Poly-crystalline	6.5% [27]
2	Malaga, Spain	-	6.1–8.0% [28]
3	Jaen, Spain	-	7.8% [29]
4	Calabria, Italy	Poly-crystalline (Si)	7.6% [30]
5	Warsaw, Poland	Thin film (amorphous-Si)	4.0-5.0% [31]
6	Umbertide, Italy	Poly-crystalline (Si)	6.2-6.7% [32]
7	Khatkar Kalan, India	Poly-crystalline (Si)	8.3% [33]
8	United Kingdom	Thin film (amorphous-Si)	3.2% [34]
9	United Kingdom	Poly-crystalline (Si)	7.5% [34]
10	United Kingdom	-	8.4% [34]
11	Brazil	Thin film (amorphous-Si)	5% [34]

Table 4. Overall average efficiencies of conventional PV plants installed worldwide.

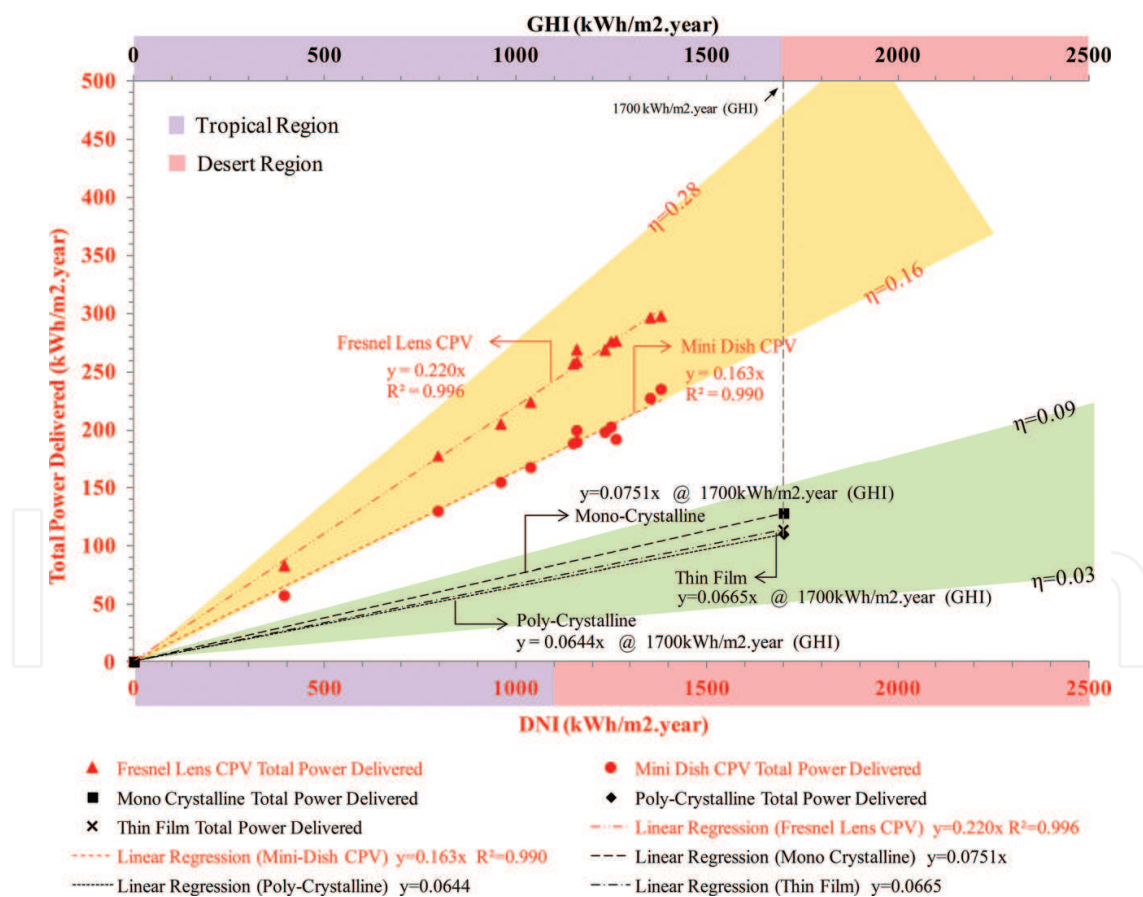


Figure 11. Total power delivered by assorted PV Systems against DNI and global irradiance [12].

of conventional PV i.e. mono crystalline, poly-crystalline and thin film, is plotted against annual average GHI of 1700 kWh/m<sup>2</sup>.year [27]. From linear regression, it can be seen that the electrical rating of photovoltaic systems is directly proportional to corresponding received

solar energy i.e. DNI for the case of CPV and GHI for the case of conventional PV. In addition, it can also be seen that the slope of linear regression line gives the long term average efficiency of respected photovoltaic technology. For Fresnel lens CPV, the slope of regressed line is 0.22 which is equal to the long term average efficiency of 22%, given in **Table 3**. The significance of **Figure 11** in the design of photovoltaic system, is that if the total DNI or GHI availability of particular region is known then the actual output of the system can be roughly estimated to have quick production potential of system in form of its electrical rating. Higher the value of solar energy input, higher the electrical rating of the system. However, for such field production estimation, only average efficiency of the system must be considered, instead of rated maximum efficiency. For desert region of Saudi Arabia, with GHI availability of 2300 kWh/m<sup>2</sup>.year [35] and assuming 90% share of beam radiations, overall output of 476 kWh/m<sup>2</sup>.year and 184 kWh/m<sup>2</sup>.year can be expected to be received from the operation of CPV and PV system, respectively, with average system efficiencies of 23 and 8%.

## 6. Summary of the chapter

The long-term electrical rating of two in-house built CPV units i.e. the mini dish and the Fresnel lens CPVs, has been successfully analyzed under the outdoor tropical weather of Singapore, which is the first ever CPV performance reporting in this region. Based on the local tropical climate conditions, the mini-dish and the Fresnel lens CPVs achieved electric ratings of 178.0 and 240.2 kWh/m<sup>2</sup>.year, which is about two folds higher than the conventional PVs (mono-crystalline, poly-crystalline and thin CIS films) of  $118 \pm 10$  kWh/m<sup>2</sup>.year, operating under the same tropical weather conditions, with only 66.1% DNI share. In addition, the average system efficiency based on the total energy input and output, for long term operation, is recommended over instantaneous maximum efficiency, as the true field performance indicator, accommodating all performance affecting parameters. The CPV system showed long term average efficiency of  $22 \pm 0.5\%$  in the tropical climate, with maximum efficiency of 28%. The plot of electric rating (in kWh/m<sup>2</sup>.year) versus the annual insolation is also suggested as its slope gives the long term average efficiency, which can be used to estimate the CPV field performance against the available solar energy (DNI). To conclude, this study demonstrates a strong potential and feasibility of CPV system operation in the tropical weather conditions. It is also emphasized that the electrical rating parameter is more accurate and reliable when conducting a performance evaluation of photovoltaic systems.

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